Rencontres de Moriond – EW – March 11 2010

# The SNO Low Energy Threshold Analysis and Combined Fits of Neutrino Oscillation Parameters

On behalf of the SNO Collaboration:

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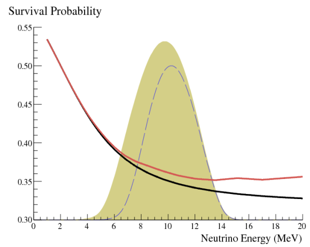
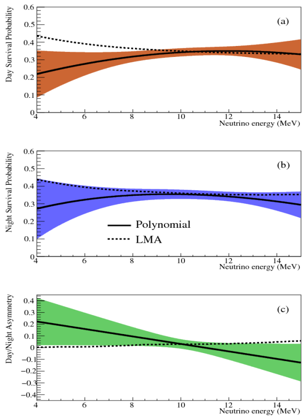
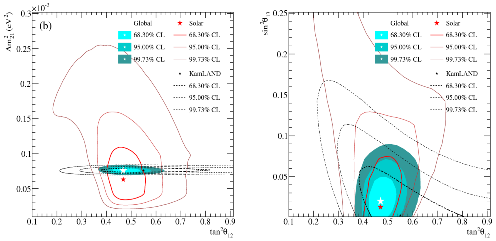
# Outline

- Motivation.
- Brief description of the SNO experiment.
- The Low Energy Threshold Analysis (LETA):
  - Basic ideas.
  - Main improvements with respect to previous SNO analyses.
- Results: neutrino fluxes and energy spectra:
  - Standard 'unconstrained' fits.
  - Survival probability as a function of neutrino energy.
- Combined fits of neutrino oscillation parameters:
  - SNO, Solar experiments, and KamLAND
  - Oscillation analysis including the effect of $\Theta_{13}$.



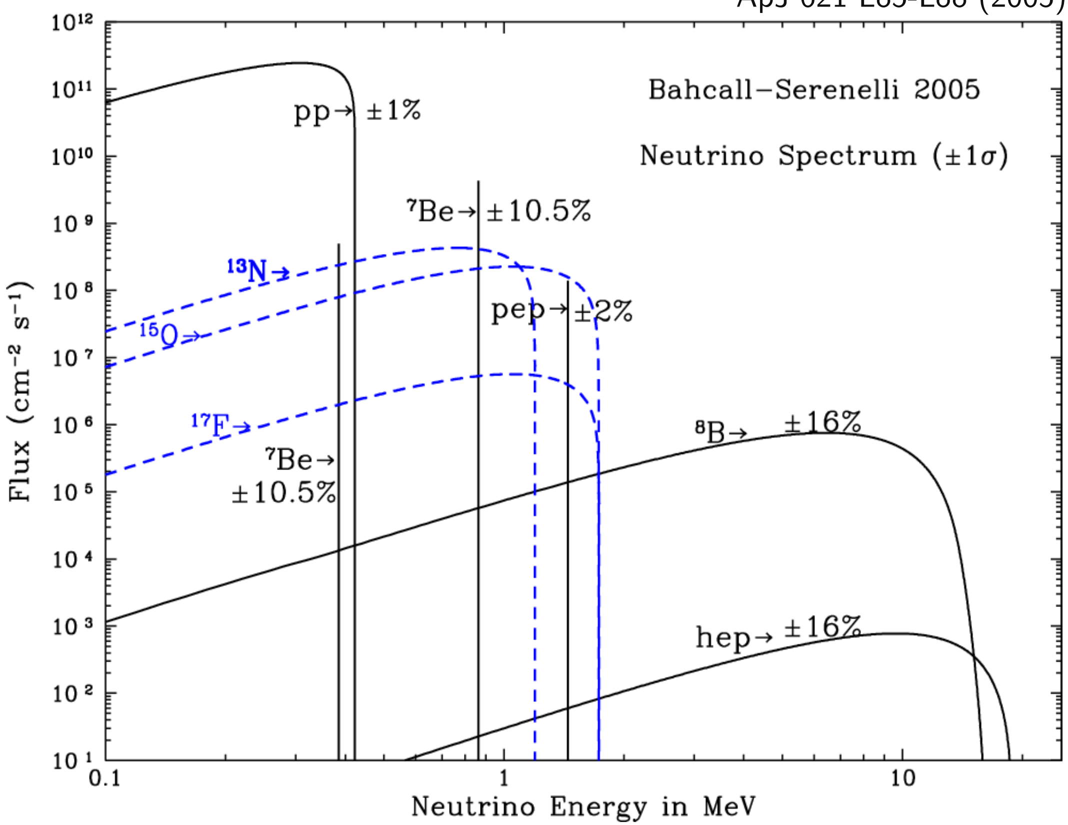



# Solar Model / Mixing

- The Standard Solar Model (SSM) describes how the Sun works.
  - One of its prediction is 8 electron neutrino fluxes and their spectra.
- Solar neutrino experiments can probe the SSM directly by measuring the electron neutrino rates on Earth.
- Flavor conversion observed by SNO in 2002.
  - SSM predictions are verified.
  - Opened a new branch of analysis: neutrino oscillations.
- Remaining improvements from SNO and other solar neutrino experiments:
  - Fluxes at high energies. Maybe discover hep neutrinos.
  - Fluxes at low energies.
  - Survival probability of electron neutrinos.
  - Precision of oscillation parameters.

ApJ 621 L85-L88 (2005)



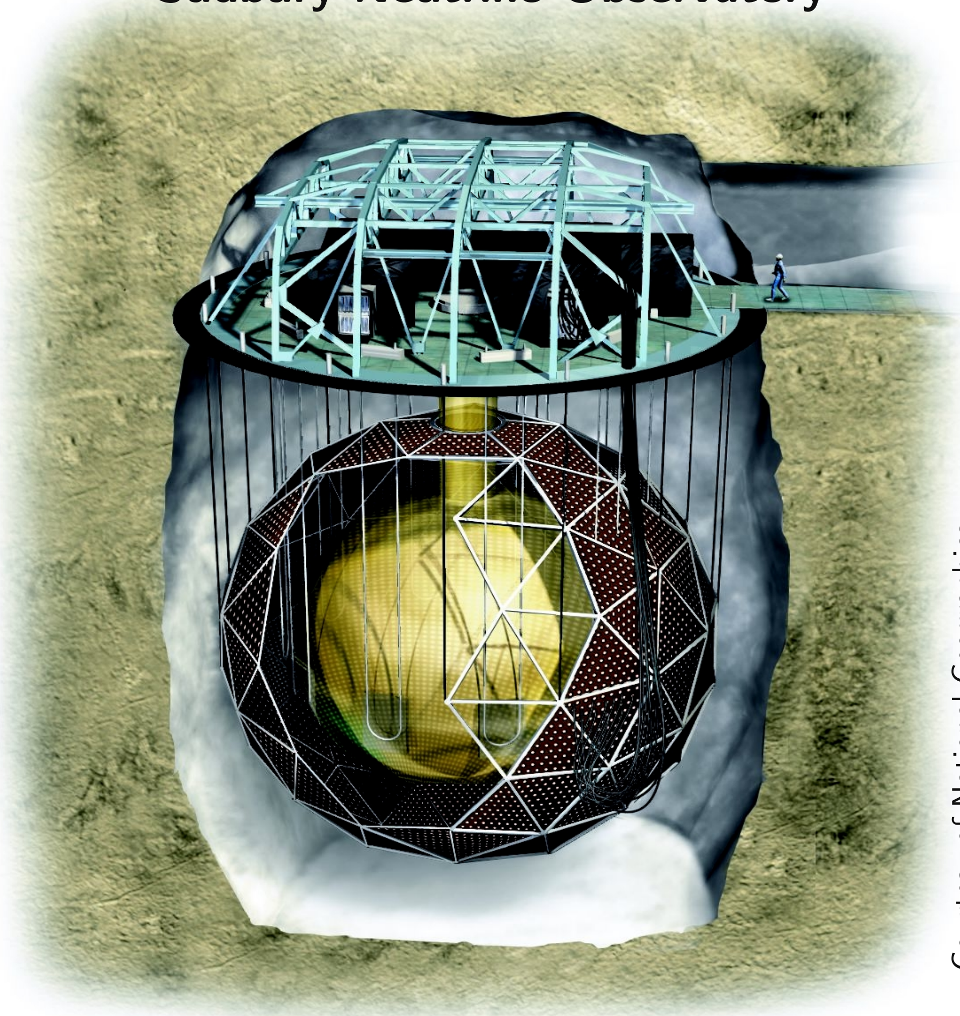

Low Energy (LE) regime:
Cl, Ga, Borexino
+ Future

High Energy (HE) regime:
Cl, SK, SNO

# SNO Detector

- Heavy water ($D_2O$) Čerenkov detector sensitive to all active neutrino flavors.
- 1kT of $D_2O$, ~7kT of $H_2O$.
- 9456 PMTs, 54% coverage.
- Low background levels:
  - Clean lab, 2km underground (Canadian shield)
  - $D_2O$: U/Th levels $< 10^{-14}$ g/g
  - $H_2O$: U/Th levels $< 5\times10^{-13}$ g/g
- Experimental program [1999-2006]:
  - 3 analysis channels, with 3 different configurations (independent phases).

**Sudbury Neutrino Observatory**



Courtesy of National Geographics

Acrylic Vessel (R = 6m)
Geodesic Support (R ~ 8.5m)

# Reactions and Phases

| $d$ = deuteron = $(p+n)$ | Phase I: Pure $D_2O$ | Phase II: +2T NaCl | Phase III: +Prop. Counters |
|---|---|---|---|
| Neutral-Current (NC): $\nu_x + d \rightarrow p + \nu_x + \boldsymbol{n}$ | $n + D_2O$<br>6.25 MeV $\gamma \rightarrow$ Č | $n + {}^{35}\mathrm{Cl}$<br>8.6 MeV $\gamma$'s $\rightarrow$ Č's | $n + {}^{3}\mathrm{He}$<br>764 keV $p,t$ |
| Charged-Current (CC): $\nu_e + d \rightarrow p + p + \boldsymbol{e\text{-}}$<br>Elastic Scattering (ES): $\nu_x + e\text{-} \rightarrow \nu_x + \boldsymbol{e\text{-}}$<br>(ES: 85% $\nu_e$) | $e\text{-} \rightarrow$ Č | $e\text{-} \rightarrow$ Č | $e\text{-} \rightarrow$ Č |

The NC measurement method is what defines the SNO Phase.

The CC and ES measurement methods do not change across phases.

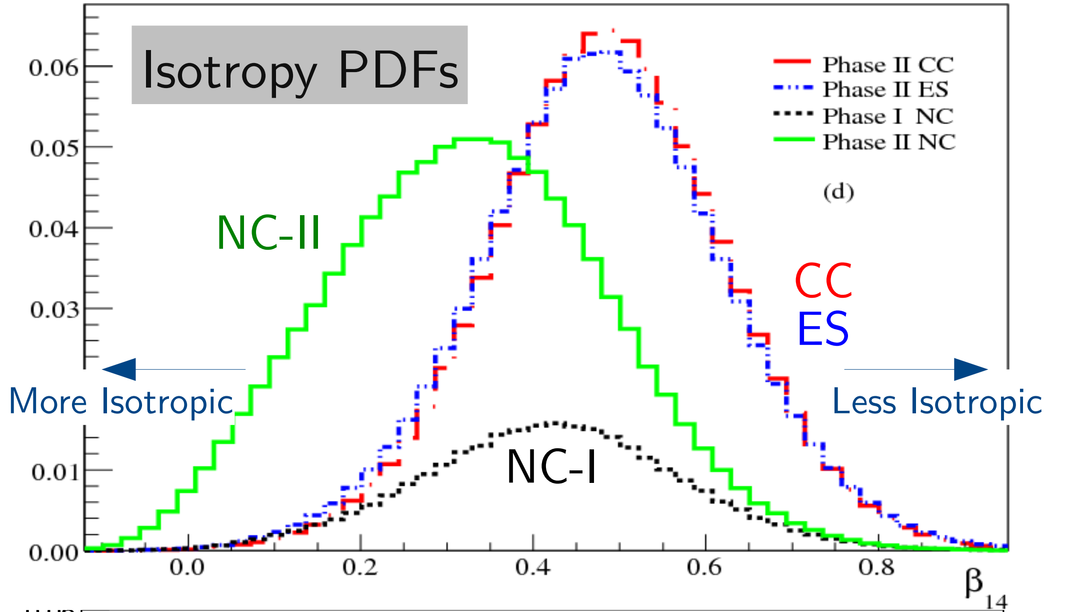
Both carry neutrino energy information.

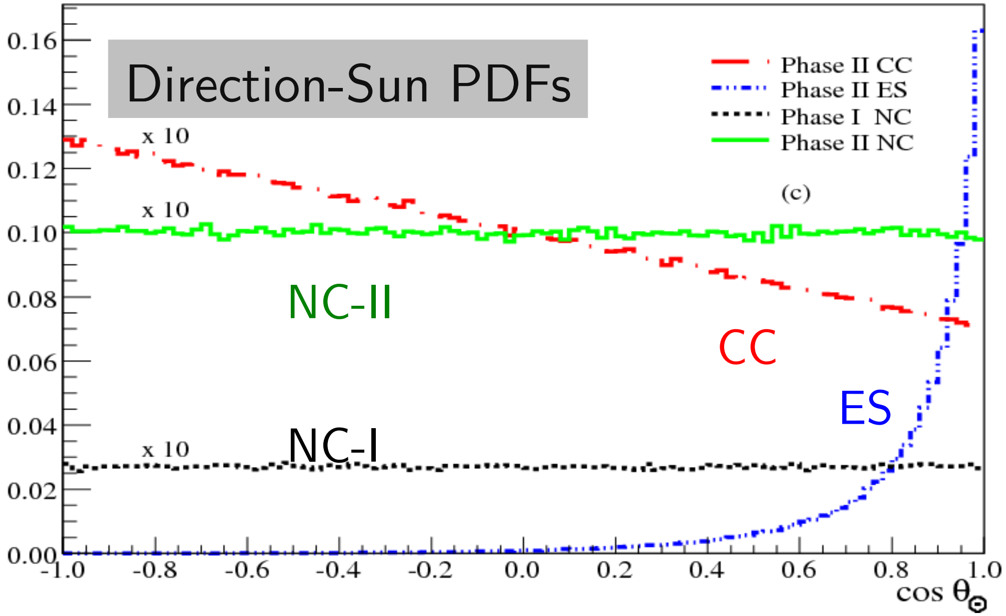
**Mostly Čerenkov light: no event-by-event identification.**

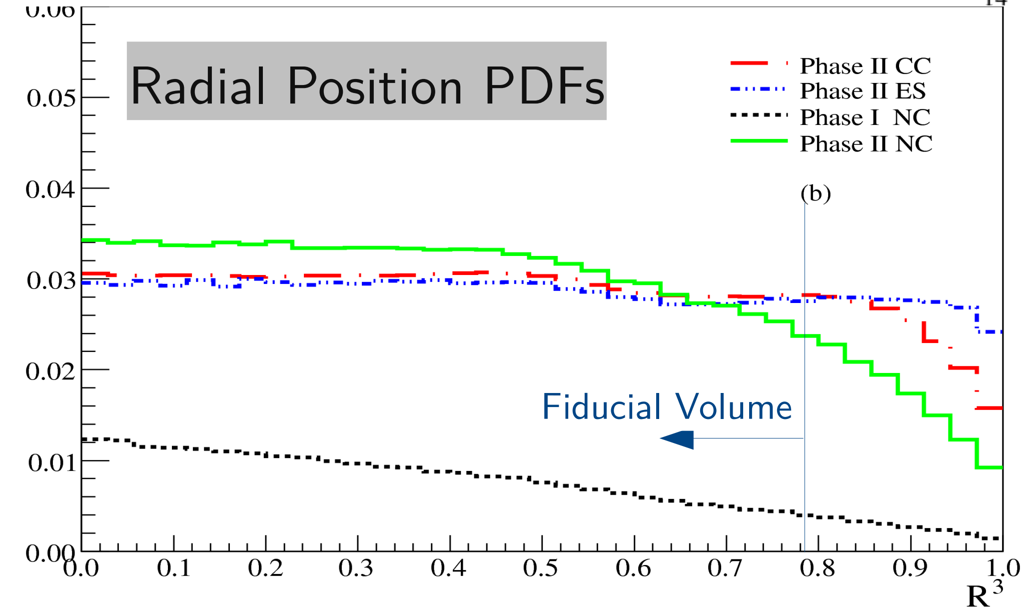
**Statistical separation is done via an extended maximum likelihood technique.**

# Statistical Separation

- All neutrino events in Phases I+II produce Č-light:
  - Separation must be made with probability density functions (PDFs) of geometrical variables from reconstruction.
  - Isotropy of PMT hits mainly separates NC(Phase II) from electron-like events.

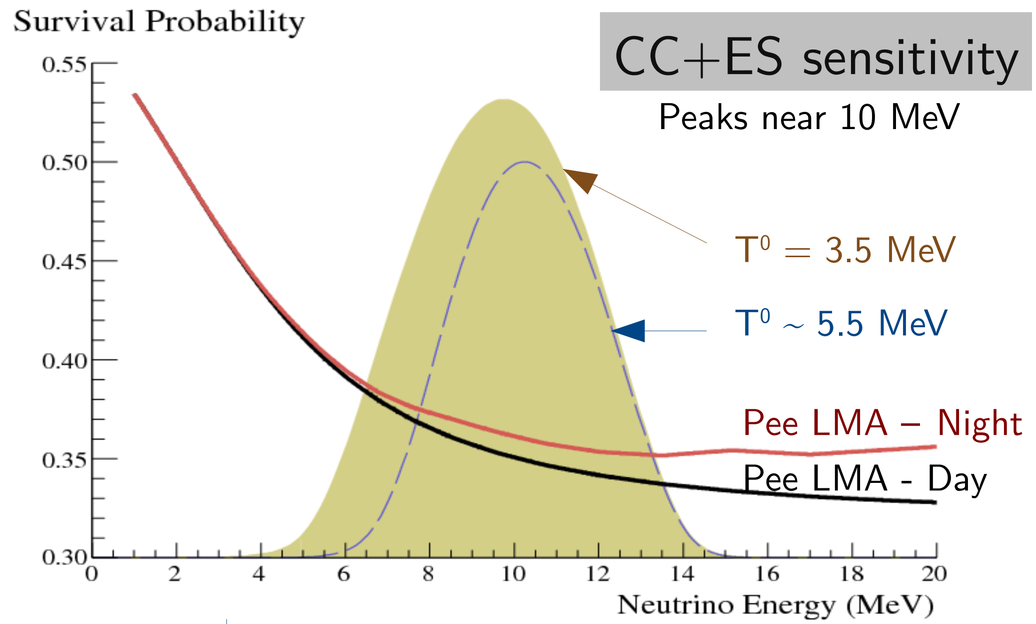


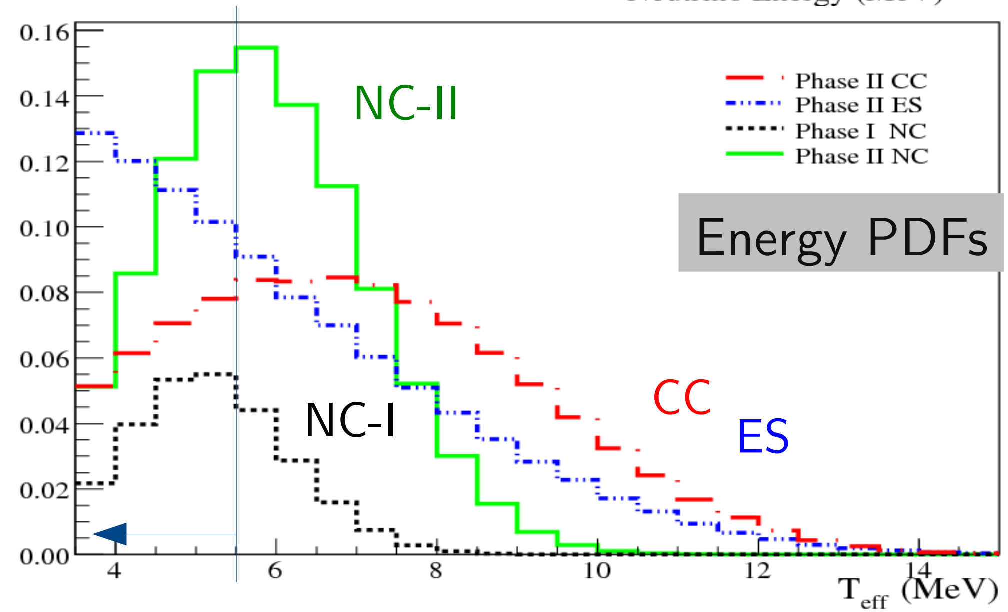



# Lowering the Analysis Threshold

- Previous thresholds (Phase):
  - 5 MeV (I), 5.5 MeV (II), 6 MeV (III)
- Lower threshold to 3.5 MeV for Phases I and II:
  - **Detector:** 100% trigger efficiency at 3.5 MeV
  - **Physics**: Enhance the sensitivity of the detector to lower energy neutrinos.
  - **Accuracy**: Increase in statistics:
    - ~70% in NC, ~30% in CC and ES.
    - Joint analysis.
- Price to pay: backgrounds.



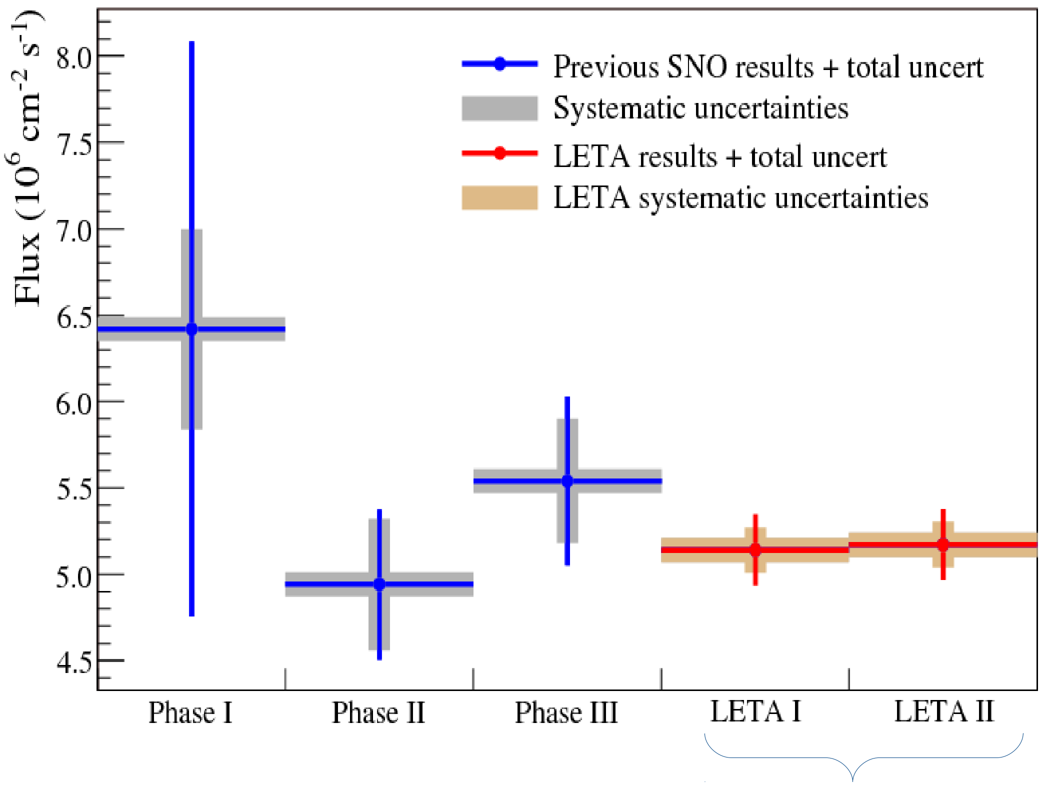



# Analysis Changes

- More background events and new sources of backgrounds.
  - 5 internal (in $D_2O$) and 12 external, across Phases I+II.
- Each source of background was carefully studied:
  - MC extensively compared to calibration sources.
- Fit background rates simultaneously with the data:
  - Constraints from detector water assays when available.
- Systematic uncertainties:
  - Dominant components (energy and isotropy) are assigned parameters that are 'floated' in the fit.
  - Others are evaluated with the standard 'shift-and-refit' method.

# NC Flux Result

- Intensive fits!
- Cross-check with different implementations of the likelihood function:
  - **Standard**: approach with binned PDFs.
  - **New**: kernel estimation, effectively smooth PDFs.
- Cross-check with different methods:
  - **Standard**: 'Unconstrained fits' where CC and ES shapes in $T_{eff}$ are determined from the data.
  - **New**: 'Constrained' fit where the survival probability is extracted directly in $E_\nu$ space.
  - Excellent agreement!
- Consistent with past phase-by-phase fluxes.
- Significant improvement in uncertainties.

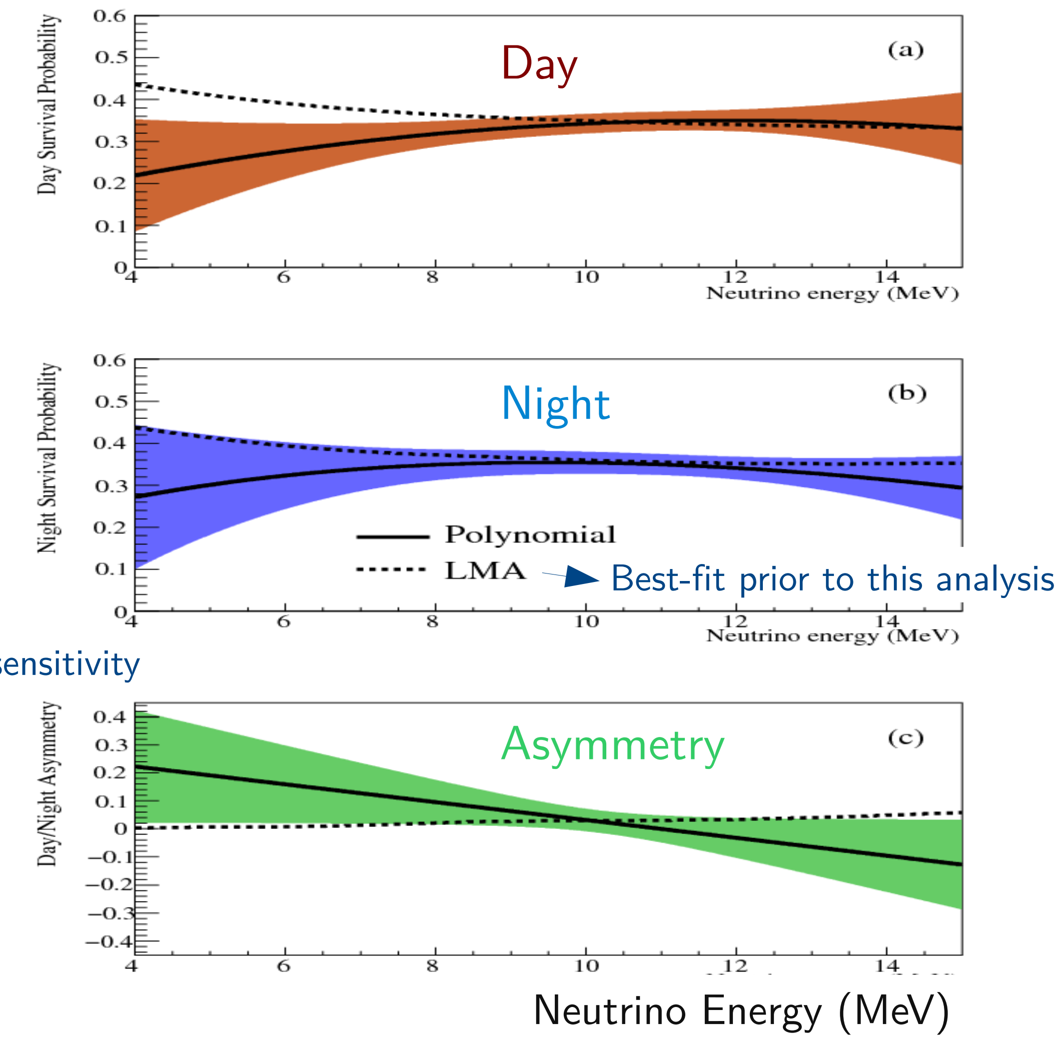



NC $= 5.14 \times 10^6$ cm$^{-2}$ s$^{-1}$ $(+4.0\ -3.8)\%$

SSM (AGSS09) $= 5.22 \pm 0.83$ (16%)

# Survival Probability Fit

- Instead of fitting fluxes by reactions, use:
  - Global flux common to all three signals.
  - Survival probability function (Pee) described by smooth analytic functions.




Peak of sensitivity

$$P_{ee}^{\text{day}}(E_\nu) = c_0 + c_1(E_\nu - 10\text{ MeV}) + c_2(E_\nu - 10\text{ MeV})^2$$

$$P_{ee}^{\text{night}}(E_\nu) = P_{ee}^{\text{day}} \times \frac{1 + A(E_\nu)/2}{1 - A(E_\nu)/2}$$

$$A(E_\nu) = a_0 + a_1(E_\nu - 10\text{ MeV})$$

Flux = $5.046 \times 10^{6}$ cm$^{-2}$ s$^{-1}$ (+3.8 −3.6)%

# Neutrino Oscillations

- Parameters of the theory on which depends an accurate calculation of Pee:

$$H_f = \frac{1}{2E_\nu}(UMU^\dagger + A)$$

**Matter effects in *A***

**Mixing angles + CP-phase**

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$M = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix}$$

**Two independent mass differences**

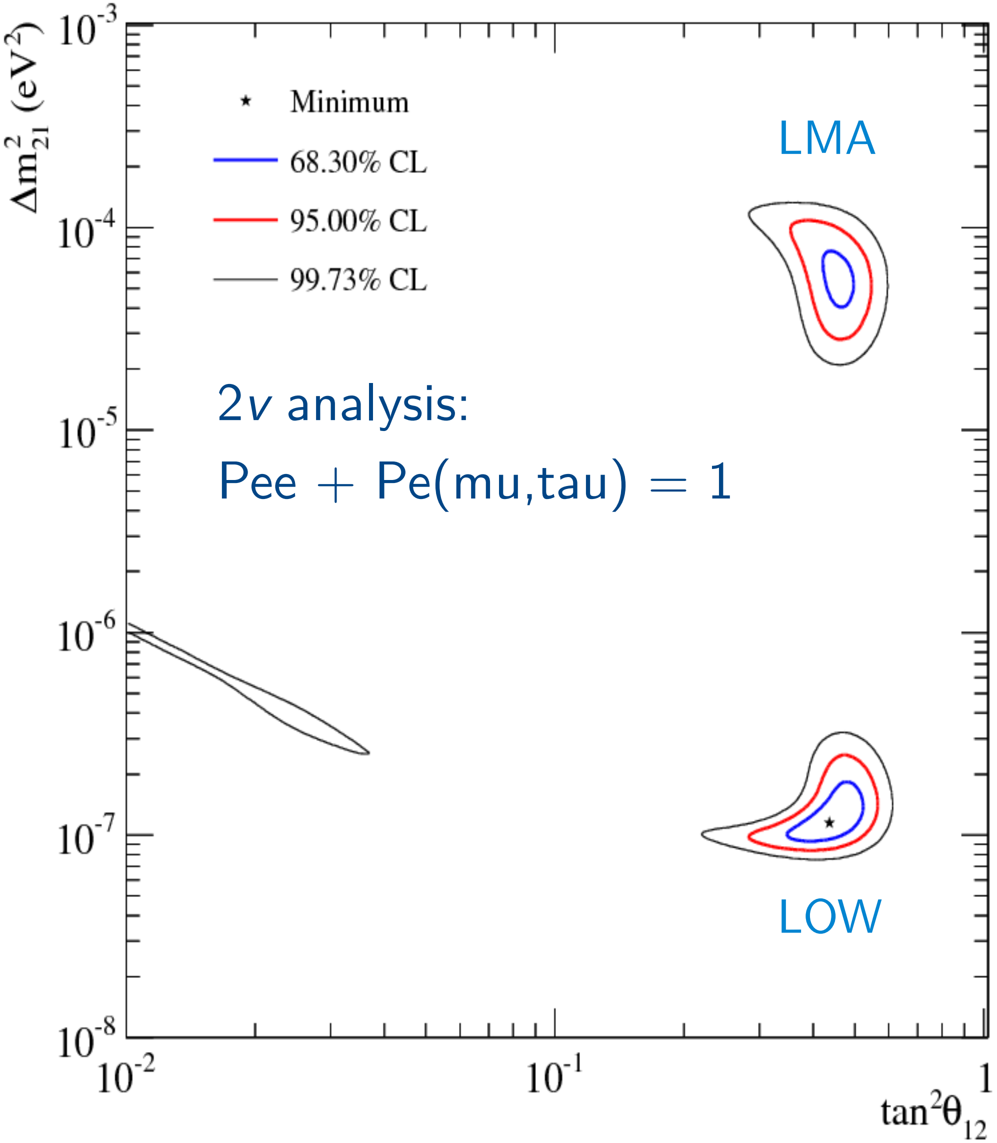
$$\Delta m^2_{kj} \equiv m^2_k - m^2_j \qquad \text{for} \quad k > j,\ k \neq j$$

$$P_{ee}(\text{solar}) \equiv P(\theta_{12}, \Delta m^2_{21}/E_\nu, \theta_{13}, \Delta m^2_{31}/E_\nu)$$

Leading — Sub-leading — Negligible

# Oscillation Analysis - SNO

- SNO-LETA part, made compact and simplistic:
  - 5 parameters only. No fluxes.
  - Test the analytic parameters from model Pee curves directly with $\chi^2$.
  - Detector response easy to handle.
- SNO: Combine LETA with the 3 fluxes from Phase-III.
  - The flux scale is re-introduced so that it is determined collectively by the 3 phases.
  - Not yet 'final 3-phase joint fit'.
- Slight preference for the LOW region.
  - Consistent with low-energy dip of measured Pee.



# Oscillation Analysis (1)

- At each point of the parameter space, the combination of all data is done at run-time, while fitting a set of secondary parameters:
  - High-energy flux scales: 8B completely free, hep constrained by the SSM width.
- The SSM fluxes, uncertainties, and correlations are enforced for the low energy neutrino fluxes.

$$\chi^2_{\text{solar}} = \chi^2_{\text{SNO}}(\phi_{^8\text{B}}) + \chi^2_{\overbrace{\text{SK,Cl,Ga,Borexino}}^{\text{Low-energy fluxes from SSM predictions}}}(\phi_{^8\text{B}}, \phi_{\text{hep}})$$

SNO systematics are fixed
SNO imposes unitarity

High-energy fluxes determined mostly by SNO and SK

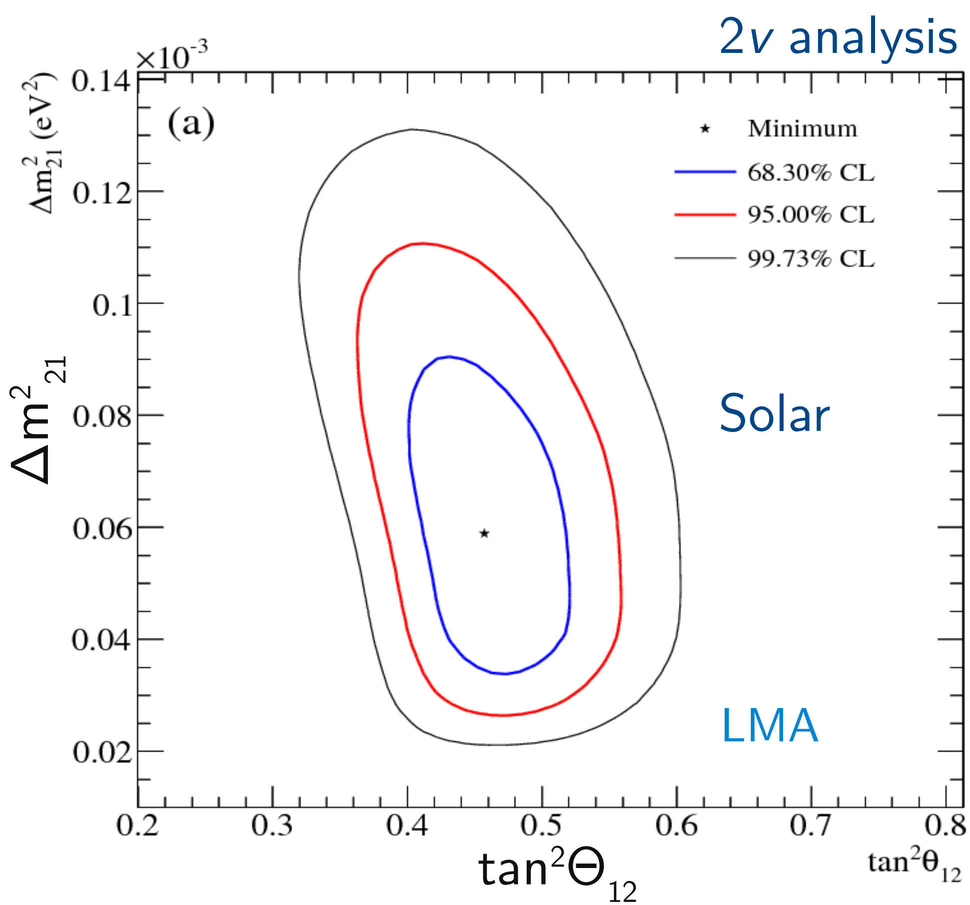
- Global fit is the same with great handle on $\Delta m^2_{21}$ due to KamLAND:

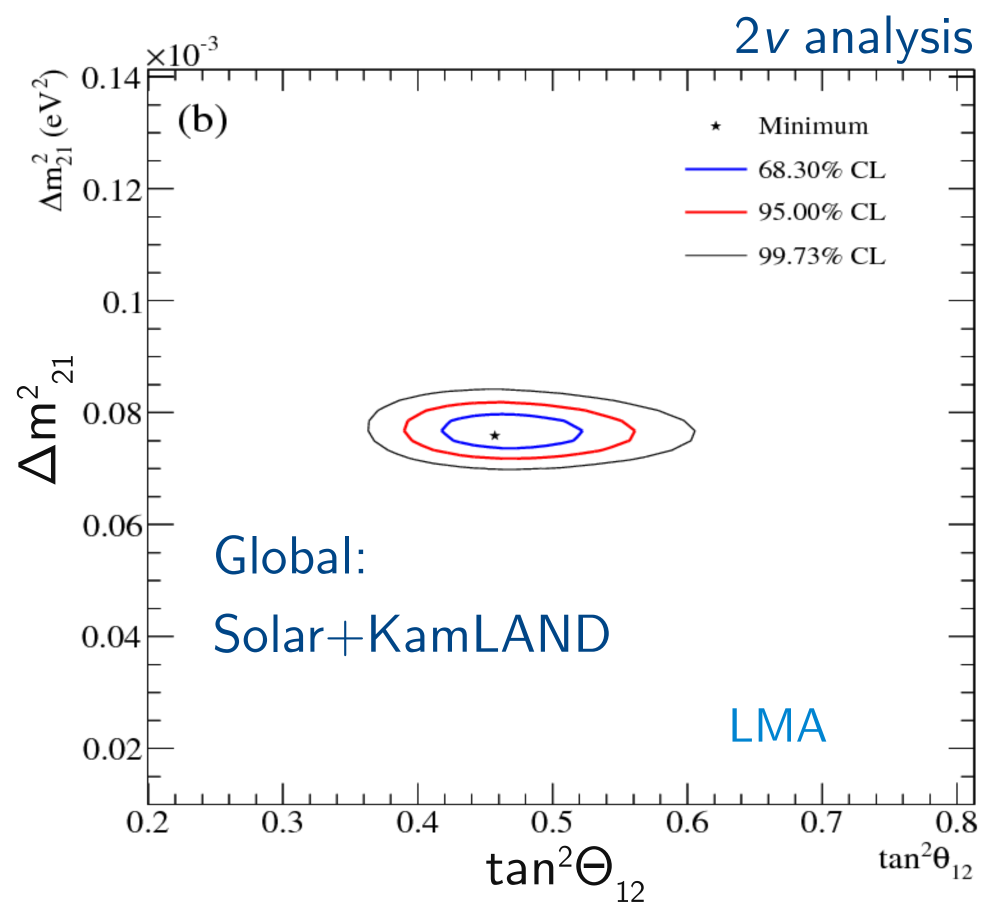
$$\chi^2 = \chi^2_{\text{solar}} + \chi^2_{\text{KamLAND}}$$

Not just 'an addition'. Actual minimization is fully done again.

# Oscillation Analysis (2)

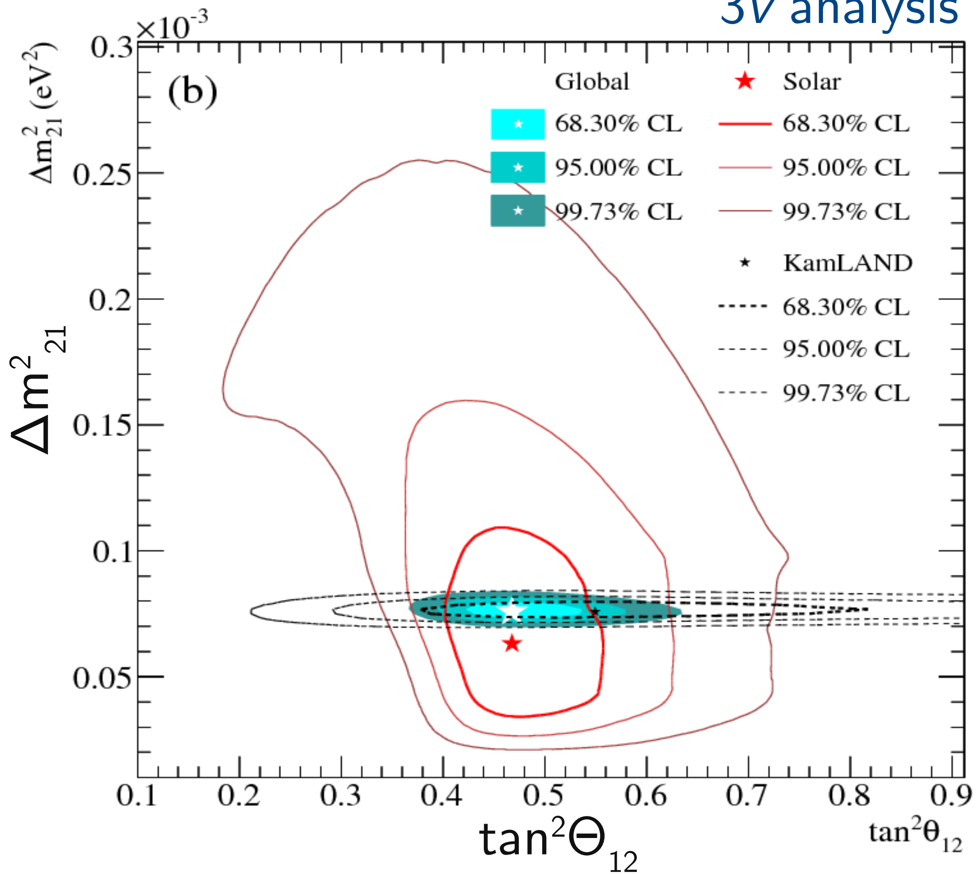
- Combine SNO with other solar experiments. The 8B flux scale is determined collectively.
- Combine all solar experiments with KamLAND.



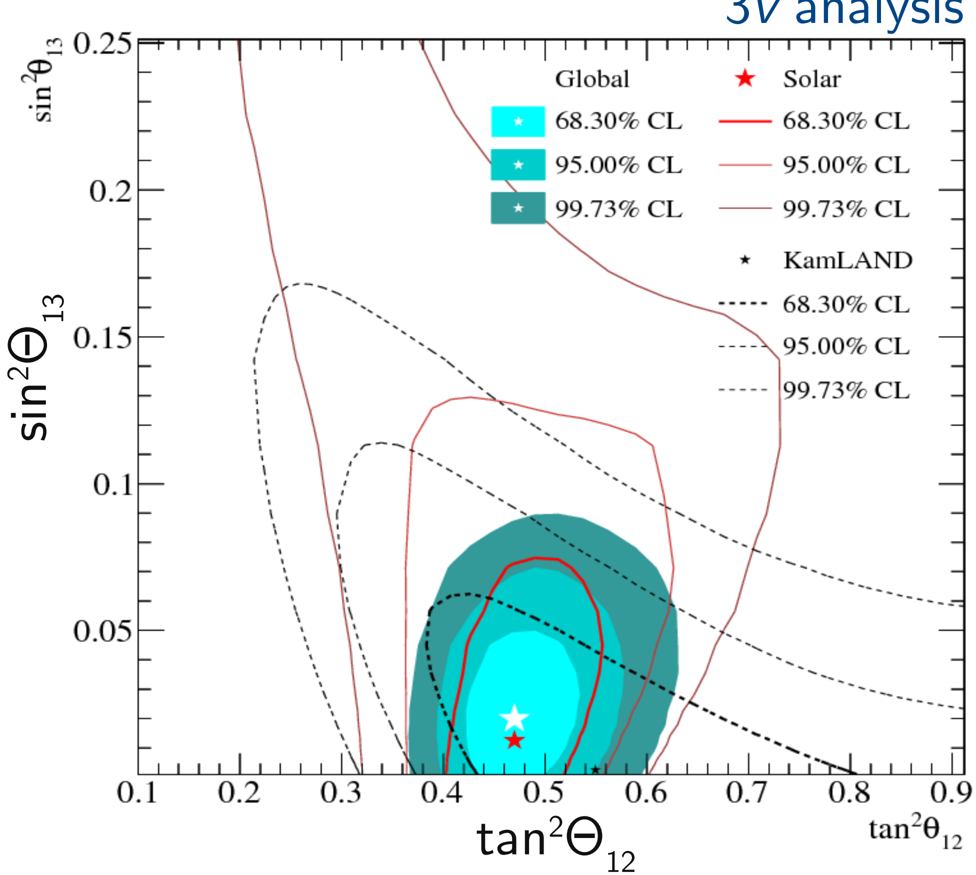



- Repeat analysis with floating $\sin^2\Theta_{13}$
- Hidden parameters have been 'minimized' away.
- Projection in the mixing angle space reveals a 'tension' between low-energy or vacuum-type oscillations and high-energy matter oscillations.

3ν analysis




3ν analysis



# Oscillation Analysis (4)

- First 'solar' hint that $\sin^2\Theta_{13}$ might be different from zero.
  - Negative side to be explored, but does not affect our result.

| Oscillation analysis | $\tan^2\theta_{12}$ | $\Delta m^2_{21}(\mathrm{eV}^2)$ |
|---|---|---|
| Solar | $0.468^{+0.052}_{-0.050}$ | $6.31^{+2.49}_{-2.58} \times 10^{-5}$ |
| Solar+KamLAND | $0.468^{+0.042}_{-0.033}$ | $7.59^{+0.21}_{-0.21} \times 10^{-5}$ |
| | $\chi^2_{\mathrm{min}}/\mathrm{ndf}$ | $\Phi_{^8\mathrm{B}}$ $(\times 10^6\ \mathrm{cm}^{-2}\,\mathrm{s}^{-1})$ |
| Solar | $67.4/89$ | $5.115^{+0.159}_{-0.193}$ |
| Solar+KamLAND | $81.4/106$ | $5.087^{+0.171}_{-0.159}$ |
| | | $\sin^2\theta_{13}(\times 10^{-2})$ |
| Solar | | $< 8.10$ (95% C.L.) |
| Solar+KamLAND | | $2.00^{+2.09}_{-1.63}$ |

$< 0.057$ (95%CL)
(similar to CHOOZ-I limit)

Table 1: Best-fit neutrino oscillation parameters and extracted $^8$B flux from a three-flavor oscillation analysis. Uncertainties listed are $\pm 1\sigma$ after the $\chi^2$ was minimized with respect to all other parameters.

# Summary / Future

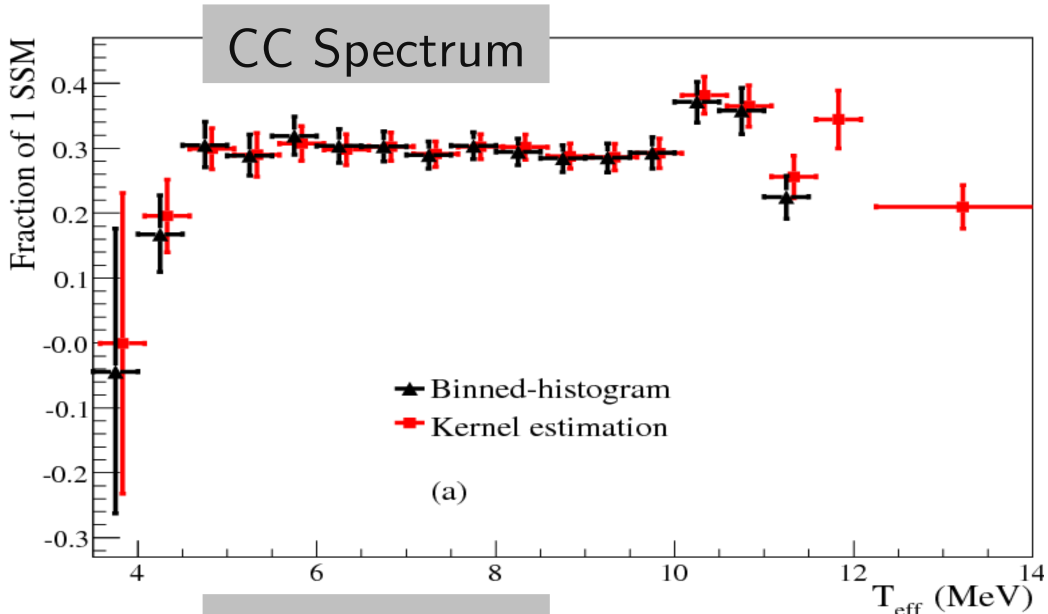
- SNO-LETA:
  - Re-analysis of Phases I+II in a more uniform framework.
  - Flux measured to ~4% total uncertainty.
  - More details in arXiv:0910.2984.
- Global Fits in Solar+KamLAND sector:
  - Solar sets the high-energy flux and $\Theta_{12}$ , KamLAND sets $\Delta m^2_{21}$ , and collectively $\Theta_{13}$ .
  - See arXiv:1001.4524 for the latest combined fits from the hep-ph world.
- Stay tuned for the SNO Three-Phase analysis results:
  - Expected to be released for the Nu2010 conference.

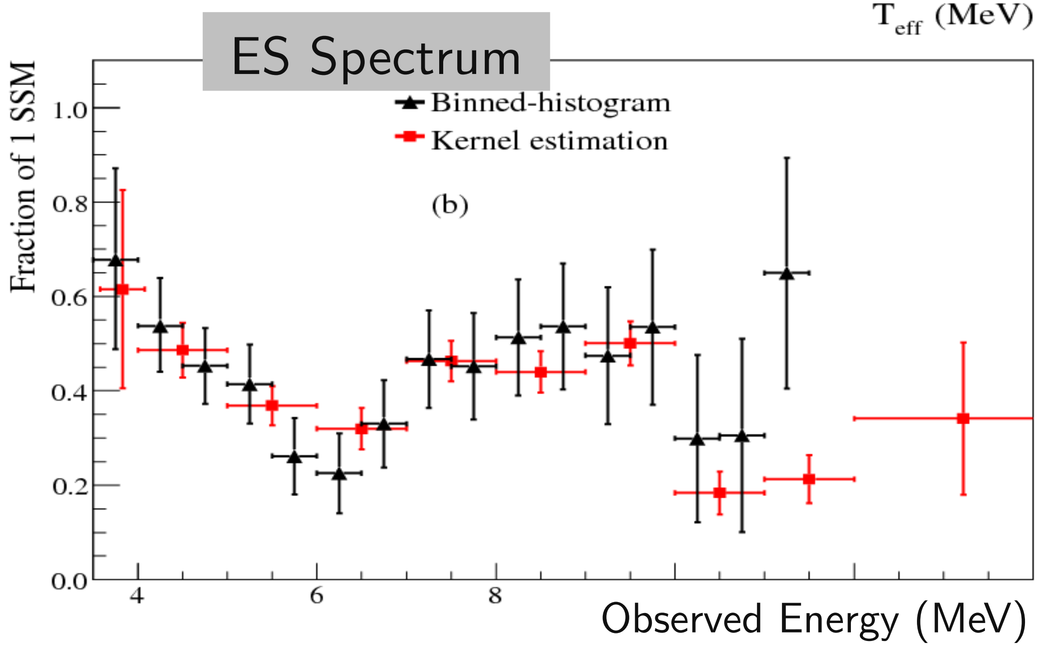
# Thank you

## Next: Additional Material

# LETA Spectrum Results

- **Observed** energy spectrum for CC and ES events.
- Spectrum presented as a fraction of the Solar Standard Model (SSM) prediction.
- Weighted average over all zenith orientations.
- Bins of 0.5MeV in Teff, larger at high energies.
- Cross-check with different implementations:
  - **Standard**: binned PDFs.
  - **New**: kernel estimation, smooth PDFs.
- Cross-check with different methods:
  - **Standard**: 'Unconstrained fits' where CC and ES shapes in $T_{eff}$ are determined from the data.
  - **New**: 'Constrained' fit where the survival probability is extracted directly in $E_\nu$ space.
- Not able to resolve the first energy bin (mostly hidden under tons of backgrounds)
- Mostly consistent with straight lines (scaling factor).



# Mixing Angle Space

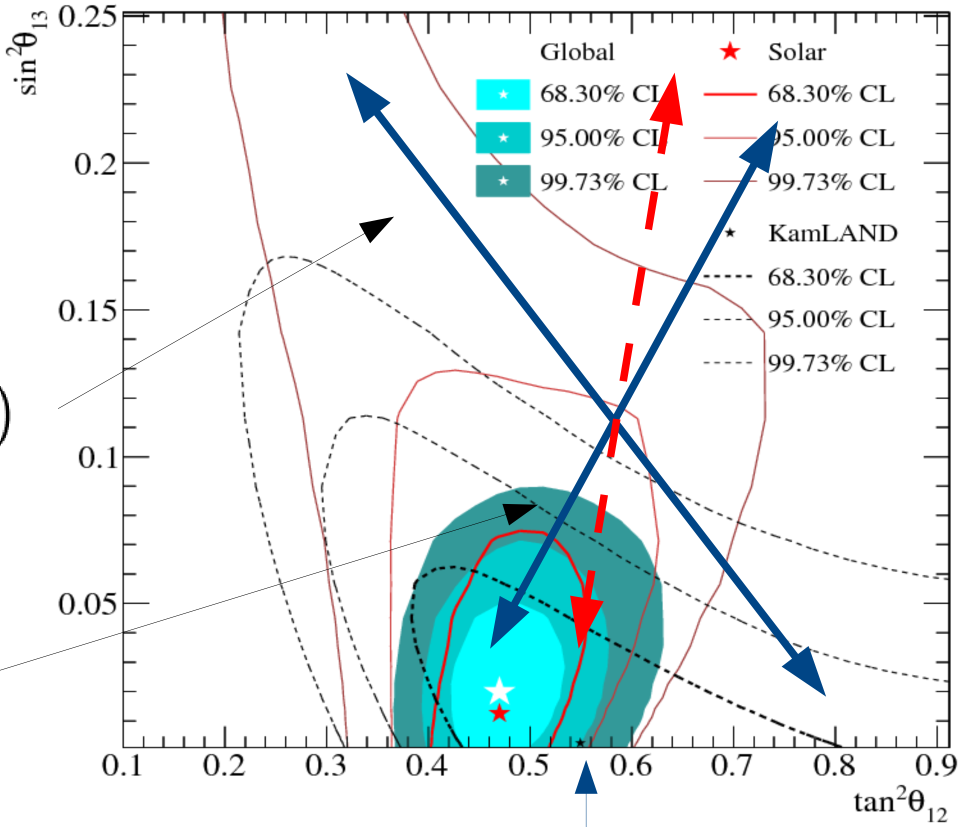
- Where is the 'tension' coming from?
  - Vacuum and matter-effects at low energy:

$$P_{ee}^{\mathrm{LE}} \sim \cos^4\theta_{13}(1-\sin^2 2\theta_{12})$$

  - Matter-effects at high energy:

$$P_{ee}^{\mathrm{HE}} \sim \cos^4\theta_{13}\sin^2\theta_{12}$$

- Each is pulling in opposite direction in $\Theta_{12}$, which produces a shift upwards in $\Theta_{13}$.




If KamLAND's own 3nu analysis differs then expect 13 to change!

# Recent and Future Analyses

- The calibration of the Sudbury Neutrino Observatory using uniformly distributed radioactive sources: arXiv:0912.2991.
- **Low Energy Threshold Analysis of the Phase I and Phase II Data Sets of the Sudbury Neutrino Observatory**: arXiv:0910.2984.
- Searches for High Frequency Variations in the $^{8}$B Solar Neutrino Flux at the Sudbury Neutrino Observatory: ApJ 701, 540-548, 2010 (arXiv:0910.2433).
- Measurement of the Cosmic Ray and Neutrino-Induced Muon Flux at the Sudbury Neutrino Observatory: Phys.Rev.D80:012001, 2009 (arXiv:0902.2776).
- Near-future publications:
  - Detailed paper describing the details of the analysis of the Phase III data published in PRL.101:111301,2008.
  - Ultimate analysis with all the solar neutrino events from SNO, including a hep neutrino analysis.
  - Complementary topics: gamma ray burst search, n-nbar events, etc.

# Abstract

The SNO Collaboration has reanalyzed the data from the first two phases of the experiment – the pure heavy water and salt phases – in order to extend the acceptance of neutral- and charged-currents, and elastic scattering events down to an observed kinetic energy of 3.5 MeV. The combined nature of the analysis, with the reassessment of the systematic uncertainties and backgrounds, has resulted in an improved determination of the neutral-current flux of $^{8}B$ solar neutrinos which is now measured with an accuracy of approximately 4%. In the context of the solar standard model and neutrino oscillation theories, the newest SNO results are of great importance in understanding the energy production in the Sun and the interaction of neutrinos with matter. A new extraction method was developed to measure the absolute $^{8}B$ flux scale and a set of analytic parameters describing the survival probability directly as a function of neutrino energy. The neutrino oscillation parameters were obtained from this new compact set of SNO-only observables, where the model survival probabilities were calculated in the context of matter-enhanced oscillations with the additional effect of $\Theta_{13}$. A collection of results from solar and reactor experiments, combined with the SNO data, resulted in a global estimation of the neutrino mixing parameters with the interesting hint that $\Theta_{13}$ might be different from zero.